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The economic impact of *Scirtothrips perseae* Nakahara (Thysanoptera: Thripidae) on California avocado production

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Abstract

In 1996, *Scirtothrips perseae* Nakahara (Thysanoptera: Thripidae) invaded California avocado orchards and moved pest management practices that relied almost exclusively on biological control to strategies dependent on insecticides to maintain thrips densities below economically damaging levels. By 1998, average losses due to thrips feeding damage in untreated infested groves reduced industry revenues by 12%. Producer costs increased by about 4.5% when *S. perseae* populations required management. In the short run (i.e., the time period during which the industry adapts to managing a new pest), producers cannot fully adapt to increases in production costs and the annual cost of *S. perseae* to producers with a thrips infestation is estimated to be \$8.65 million (US). In the long run (i.e., the time period after which the industry has fully adapted to the effects of a new pest), producers are able to fully reallocate resources to their most efficient use and the annual cost of *S. perseae* is calculated to be \$5.22 million (US) per year. For the entire USA avocado industry, the annual short-run loss attributable to *S. perseae* in California is calculated to be \$8.51 million (US) and \$4.45 million (US) in the long run.

Keywords: Economic analysis; Exotic pest; Avocado; *Scirtothrips perseae*

1. Introduction

The introduction of an exotic pest of agricultural importance can cause significant economic damage because of explosive population growth, which results in part, because the natural enemies that control the pest in its native environment are missing in the new environment. Economic damage resulting from an exotic pest can include reduced yields and produce quality, increased incidence of disease, or higher pest control costs.

In June 1996, *Scirtothrips perseae* Nakahara (Thysanoptera: Thripidae), a pest native to Mexico and Guatemala, was discovered damaging foliage and fruit of Hass avocado, *Persea americana* var. *drymifolia* Blake (Lauraceae) in Ventura County, CA, USA (Nakahara, 1997; Hoddle et al., 2002a). Heavily infested orchards in Ventura County experienced 50–80% crop damage in 1997 and fruit was either unmarketable or downgraded in packing houses (Hoddle and Morse, 1997, 1998). By May 1998, *S. perseae* infested 80% of California avocado acreage (Hoddle et al., 1998) and pest densities were highest in areas with a cool coastal climate (Hoddle, 2002a). Currently, approximately 95% of fruit bearing acreage has this pest and around 80% of producers experience economic losses to *S. perseae* (Hoddle unpublished).

Immature avocado leaves and fruit are preferred feeding and oviposition sites for *S. perseae* (Hoddle et al., 2002b). Feeding damage by high densities of *S. perseae* larvae and adults over the late fall through spring period can result in defoliation. However, the main source of economic loss attributable to *S. perseae* is scarring of immature fruit in spring by feeding thrips. Scarring $\geqslant 5\%$ of the fruit surface by feeding thrips results in economic loses to producers (Phillips, 1997).

Before the introduction of *S. perseae*, arthropod biological control succeeded in California avocado

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orchards because of minimal pesticide use (McMurtry, 1992) and a variety of mite and insect pests have been kept below economically injurious levels by natural enemies in California (Fleschner, 1953; Fleschner et al., 1955). However, biological control of this pest complex is now threatened by *S. perseae* as producers have resorted to regular pesticide applications to reduce fruit damage caused by thrips. Efforts to register new reduced-risk pesticides for *S. perseae* control on avocados are underway (Hoddle and Morse, 1998).

Avocados are an economically important crop in California and the harvest in 1999–2000 was worth $339 million (US) for both Hass and other varieties of avocados (California Avocado Commission, 2000). California currently produces about 78% of total USA production of all avocados and accounts for 88% of the USA supply of the high-value Hass avocados. Hass avocados account for about 80% of California production and California is the only producer of Hass avocados in the USA. Florida and Hawaii are major producers of other varieties of avocados.

The USA is an importer of high-quality Hass avocados and an exporter of other avocado varieties. Prior to 1998, Chile was the main exporter of Hass fruit to the USA. However, in 1998, the Mexican Hass Avocado Agreement, allowing restricted imports of Hass from Mexico, was negotiated between Mexico and the USA. Chile and Mexico are now the major suppliers of Hass imports into the USA. Florida and Hawaii export about 81% of the other varieties of avocados grown in those states. California is not a significant source of exports of either Hass or other varieties of avocados.

Economic losses are incurred when avocado fruit disfigured by thrips feeding is either culled or down graded in packing houses after harvest, or when producers apply insecticides in an attempt to reduce thrips populations to non-damaging densities. When an agricultural industry has a large share of the market, increases in producer costs may cause a change in market prices and supplies. A market equilibrium graph (Fig. 1) shows how increases in production costs influence changes in market quantity and price. Market quantity is measured along the horizontal axis and price along the vertical axis. Supply curves are labeled *S* and are upward sloping because increases in market prices will cause producers to produce more. The demand curve is labeled *D* and is downward sloping because increases in prices will cause people to want less of a commodity. The original market equilibrium is point a, quantity supplied is Q' and the market price is P' (Fig. 1).

The establishment of *S. perseae* causes economic losses to producers from increases in pest control costs. The increased production costs cause the industry supply curve to shift up from S' to S'' by ΔC. This shift up in the supply curve moves the market equilibrium from point *a* to point *b*. Quantity supplied falls from Q' to Q'' and market prices rise from P' to P'' (Fig. 1).

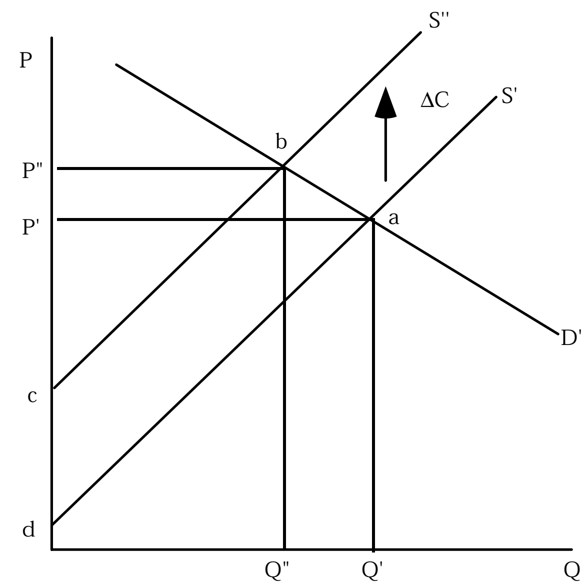

Fig. 1. Effect of *Scirtothrips perseae* establishment on avocado prices and quantity. S = supply, D = demand, Q = quantity, P = market price, a = original, pre-infestation, market equilibrium, b = post-infestation market equilibrium, c = intercept of post-infestation supply curve, d = intercept of pre-infestation supply curve.

From the changes in market quantity and price, the losses to producers may be calculated as the change in producer welfare. Producer welfare is the difference between the value producers receive for a particular good and the cost of producing it. It is the area below the market price and above the supply curve. Total producer welfare before the thrips infestation is equal to area $P'ad$. After *S. perseae* established, total producer welfare became equal to area $P''bc$. The net loss to producers is equal to area *abcd* (see Nicholson, 1998 for more details).

Because the upward shift in the supply curve due to *S. perseae* damage and management affects USA market prices for avocados, uninfested producers in other regions are also affected by the pest's introduction, even though the pest is not established there. With no increase in control costs, higher market prices will benefit those producers without *S. perseae* infestations. Consequently, the total economic effect on the USA avocado industry depends on changes in producer costs, market supply, and market prices. This study analyzes fruit quality and pest management data to estimate the change in the USA avocado market quantity and price. We use these results to estimate the total economic impact of *S. perseae* on avocado producers in infested and uninfested regions in the USA.

2. Materials and methods

2.1. Economic analyses and modeling

An equilibrium displacement model was used to calculate the changes in market prices and quantities to determine the new market equilibrium and the losses in producer welfare. In this model, a system of demand and supply equations are laid out to determine how quantity supplied, prices, and production changes in response to an exogenous change (i.e., the establishment of an exotic pest) in production costs that cause an upward shift of the supply curve (Alston et al., 1995; Lichtenberg et al., 1988). The model used is parameterized with market and biological data.

This model does not predict what the actual market quantities and prices will be after a pest establishes because many factors influence actual production (such as temperature, or whether trees are exhibiting alternate bearing, etc.) and market supplies each year. Rather, this model allows the economic effects of an exotic pest introduction to be uniquely determined at a point in time given market conditions and production costs at that point in time.

The first set of equations below characterizes the demand side of the market. Demand is separated into demand for Hass avocados, D_h (Eq. (1.1)) and other varieties, D_0 (Eq. (1.2)). Quantity demanded for each variety is a function of the prices of both Hass avocados, P_h, and other varieties, P_o

$$D_h = d_h(P_h, P_o), \tag{1.1}$$

$$D_o = d_o(P_h, P_o). \tag{1.2}$$

The next sets of equations characterize the supply side of the market for Hass avocados. Within the USA, Hass avocados are produced only in California and imported Hass fruit augments this supply. The total supply of Hass, S_h, is equal to California production by producers infested with thrips, T_{hic}, California production by producers uninfested with thrips, T_{huc}, plus imports, M_h (Eq. (1.3)). California production by infested producers, T_{hic}, is a function of the price producers receive for their output, P_h, and the costs of production, C_h (Eq. (1.4)). California production by uninfested producers is only a function of the price producers receive for their output, P_h (Eq. (1.5)). Because costs do not change for producers who do not experience a thrips infestation, the cost term is not included. Import quantity, M_h is a function of the USA market price for Hass, P_h (Eq. (1.6)).

$$S_h = T_{hic} + T_{huc} + M_h, \tag{1.3}$$

$$T_{hic} = t_{hic}(P_h, C_h), \tag{1.4}$$

$$T_{huc} = t_{huc}(P_h), \tag{1.5}$$

$$M_h = m_h(P_h). \tag{1.6}$$

The total supply of other avocado varieties, S_o, is equal to total production of other varieties from California by infested producers, T_{oic}, by uninfested producers in California, T_{ouc}, and supply from the rest of the USA, S_{orus} (Eq. (1.7)). California production by infested producers, T_{oic}, is a function of the market price, P_o, and costs of production, C_o (Eq. (1.8)). California production by uninfested producers, T_{ouc}, is a function only of the market price (Eq. (1.9)). Florida and Hawaii export other varieties of avocados so supply by this region to the USA is equal to total production, T_{orus}, less exports, E_o (Eq. (1.10)). Total production and exports of other varieties are a function of USA market prices of other varieties (Eqs. (1.11) and (1.12)). Other, non-Hass, varieties of avocados are not imported into the USA.

$$S_o = T_{oic} + T_{ouc} + S_{orus}, \tag{1.7}$$

$$T_{oic} = t_{oic}(P_o, C_o), \tag{1.8}$$

$$T_{ouc} = t_{ouc}(P_o), \tag{1.9}$$

$$S_{orus} = T_{orus} - E_o, \tag{1.10}$$

$$T_{orus} = t_{orus}(P_o), \tag{1.11}$$

$$E_o = e_o(P_o). \tag{1.12}$$

The final two equations are the market equilibrium conditions that state that the quantity demanded of Hass, D_h, must equal the quantity supplied of Hass, S_h, (Eq. (1.13)) and the quantity demanded of other varieties, D_o, must equal the quantity supplied, S_o (Eq. (1.14)).

$$D_h = S_h, \tag{1.13}$$

$$D_o = S_o. \tag{1.14}$$

This model assumes that regions currently free of thrips will not become infested. Within California, uninfested regions do not have a climate hospitable to thrips. Outside of California, thrips cannot spread naturally due to natural barriers such as oceans or the absence of host material, or hot humid environments which *S. perseae* cannot tolerate.

The log differential of Eqs. (1.1)–(1.14) was taken and the equations were then expressed in terms of elasticities and percentage changes. An elasticity measures the percentage change in a quantity variable for a 1% change in a price variable. Using elasticities and percentage changes provide a unit free method of calculating changes in market quantity and price variables.

The converted equations are:

$$\hat{D}_h - \eta_{hh}\hat{P}_h - \eta_{ho}\hat{P}_o = 0, \tag{2.1}$$

$$\hat{D}_o - \eta_{oh}\hat{P}_h - \eta_{oo}\hat{P}_o = 0, \tag{2.2}$$

$$S_h - \lambda_{hic}\hat{T}_{hic} - \lambda_{huc}\hat{T}_{huc} - \lambda_{hm}\hat{M}_h = 0, \tag{2.3}$$

$$\hat{T}_{hic} - \varepsilon_{hc}\hat{P}_h = -\varepsilon_{hc}\hat{C}_h, \tag{2.4}$$

$$\hat{T}_{huc} - \varepsilon_{hc}\hat{P}_h = 0, \tag{2.5}$$

$$\hat{M}_h - \varepsilon_{hm}\hat{P}_h = 0, \tag{2.6}$$

$$\hat{S}_o - \lambda_{oic}\hat{T}_{oic} - \lambda_{ouc}\hat{T}_{ouc} - \lambda_{orus}\hat{S}_{orus} = 0, \tag{2.7}$$

$$\hat{T}_{oic} - \varepsilon_{oc}\hat{P}_o = -\varepsilon_{oc}\hat{C}_o, \tag{2.8}$$

$$\hat{T}_{ouc} - \varepsilon_{oc}\hat{P}_o = -\varepsilon_{oc}\hat{C}_o, \tag{2.9}$$

$$\hat{T}_{orus} - \gamma_{ous}\hat{S}_{orus} - \gamma_{oe}\hat{E}_o = 0, \tag{2.10}$$

$$\hat{T}_{orus} - \varepsilon_{orus}\hat{P}_o = 0, \tag{2.11}$$

$$\hat{E}_o - \varepsilon_{oe}\hat{P}_o = 0, \tag{2.12}$$

$$\hat{D}_h - \hat{S}_h = 0, \tag{2.13}$$

$$\hat{D}_o - \hat{S}_o = 0. \tag{2.14}$$

where η_{hh} is the Hass own-price elasticity of demand, η_{ho}, is the Hass cross-price elasticity of demand, η_{oh} is the other varieties own-price elasticity of demand, η_{oo} is the other varieties cross-price elasticity of demand, ε_{hc} is the elasticity of supply for Hass avocados from California, ε_{hm} is the elasticity of import trade for Hass avocados, ε_{oc} is the elasticity of supply for other varieties from California, ε_{orus} is the elasticity of supply for other varieties of avocados produced by Florida and Hawaii, ε_{oe} is the elasticity of supply for exports, λ_{hic} is the share of Hass avocados from California in the USA market produced by producers who experience a thrips infestation, λ_{huc} is the share of Hass avocados produced by California producers whose groves remain uninfested, λ_{hm} is the share of imported Hass in the USA market, λ_{oic} is the share of other non-Hass avocado varieties from California in the USA market produced by producers who have a thrips infestation, λ_{ouc} is the share of other non-Hass avocado varieties from California produced by producers whose groves remain uninfested, λ_{orus} is the share of other non-Hass varieties from Florida and Hawaii in the USA market, γ_{ous} is the share of production from Florida and Hawaii that is marketed in the USA, and γ_{oe} is the share of production from Florida and Hawaii that is exported to other countries.

The own-price elasticity of demand measures the percentage change in quantity demanded for a commodity when the price of that commodity changes by 1%. The cross-price elasticity of demand measures the percentage change in quantity demanded for a commodity when the price of another commodity changes by 1%. The elasticity of demand is negative for own-price effects and positive for cross-price effects. Therefore, if the price of Hass avocados increases, the demand for Hass avocados decreases and the demand for other varieties increases.

The elasticities of supply for quantities destined for the USA market and production are positive. The elasticities of supply with respect to input costs and exports are negative. Therefore, if USA market prices rise, USA production increases, Hass imports increase, and Hass exports decrease. If production costs increase, California avocado production decreases.

In the short run, some factors of production (such as land) are fixed for producers and they have limited choices in responding to a newly arrived pest. This is especially true for producers of perennial crops because large capital outlays are required to plant or remove an orchard from production. Changes in market supply may come through acreage reductions, but more typically from changes in harvesting and packing efforts. Therefore, the elasticity of supply is relatively low in the short run. In the long run, producers have more flexibility in adapting to infestations of exotic pests and production factors can be moved into other uses such as growing alternative crops. Long-run changes in market quantities generally occur through reductions of productive acreage, which cause an increase in market prices because of reduced supply. The long run is the time period by which the industry has fully adapted to the effects of an exotic pest introduction because the industry has adapted to changes in costs associated with this pest. Because producers have more flexibility in the long run, elasticity of supply is higher in the long-run and losses in the long-run will be lower than the immediate impacts incurred in the short-run. By setting the elasticity of supply at different levels in the model, producer losses may be estimated for both the short- and the long-run time period.

The model described by Eqs. (2.1)–(2.14) has 14 equations and 14 unknown, endogenous variables. The endogenous variables are the percentage change in market quantity variables, $\hat{D}_h$, $\hat{D}_o$, $\hat{S}_h$, $\hat{S}_o$, $\hat{S}_{orus}$, $\hat{T}_{hic}$, $\hat{T}_{huc}$, $\hat{T}_{oic}$, $\hat{T}_{ouc}$, $\hat{T}_{orus}$, $\hat{M}_h$, $\hat{E}_o$, and the percentage change in price variables $\hat{P}_h$, $\hat{P}_o$. The parameters of the model are the demand elasticities η_{hh}, η_{ho}, η_{oh}, η_{oo}; the supply elasticities ε_{hc}, ε_{hm}, ε_{oc}, ε_{orus}, ε_{oe}; the market shares λ_{hic}, λ_{huc}, λ_{hm}, λ_{oic}, λ_{ouc}, λ_{orus}; and the production shares γ_{ous}, γ_{oe}. The exogenous shock to the initial market equilibrium is the percentage increase in costs of production per ton for infested orchards of Hass avocados $\hat{C}_h$ and other varieties $\hat{C}_o$.

The percentage change in the endogenous variables may be calculated by substituting equations and solving for individual variables, or, more easily, using matrix algebra (see Alston et al., 1995, pp. 257–260 for a comparison of methods). This model was solved using matrix algebra programmed in MatLab (Mathworks, 1999).

2.2. Determination of thrips control costs and $\hat{C}$

The control costs reported in this study were those incurred for a typical California avocado producer in 2001. The year 2001 was used because it was the first year during which treatment programs had been fully developed and implemented. Sixty-two avocado producers in Ventura and San Diego Counties, CA, USA, answered questionnaires on the nature of commercial *S. perseae* treatment programs. The questionnaires asked producers if they had a thrips infestation, if they treated the infestation, the number of treatments completed, what was used for each treatment, and whether the orchard was located within five miles, 10 miles or further inland from the California coast (*S. perseae* severity is affected by orchard location relative to the coast (Hoddle, 2002a)).

At the time of the survey, growers could treat orchards with one of three insecticides recommended for use against *S. perseae*. During 2001, abamectin (Agri-Mek, Syngenta, Greensboro, NC) was the most commonly used insecticide, followed by spinosad (Success, Dow AgroSciences, Indianapolis, IN), then sabadilla (Veratran-D, Dunhill Chemical Co., Rosemead, CA). If a producer treated for *S. perseae*, usually one application of an insecticide was used for pest control. When more than one application was made, it was typically a chemical that differed from the first insecticide sprayed. Alternating insecticides is practiced to prevent the development of pesticide resistance by *S. perseae*.

Agricultural pest control companies in Ventura and San Diego were contacted for the price of materials and application fees for each type of thrips control treatment listed by producers in completed surveys. Because the large majority of thrips treatments used abamectin, the cost of applying abamectin was used to calculate the percentage increase in the total costs of production to grow avocados.

Abamectin was usually applied to avocados by helicopter with 1–2% NR-415 insecticidal oil (Leffingwell, Kirkland, Washington) added. The total cost of abamectin, oil, and application expense, was approximately \$180 per acre per treatment. Treating *S. perseae* with abamectin effectively eliminated quality damage for producers who applied this product correctly.

The percentage increase in industry costs was calculated by dividing the increase in producer costs per ton by the total producer costs per ton before the establishment of *S. perseae*. Budgets developed by Takele (1992) and the California Avocado Commission (1998, 1999, 2000) provided data on pre-infestation producer costs. Analysis of data from these two budgets indicated that the percentage increase in production costs was 4.5% for growers who treated *S. perseae* infestations.

2.3. Model parameterization

The model parameters of interest are the demand and supply elasticities, and the market and production shares. Demand and supply elasticities for the California avocado industry were obtained from Carmen and Craft (1998) (Table 1). In that analysis, the estimated demand elasticities were for Hass and other avocado varieties combined. Techniques developed by Armington (1969) were used to obtain the own- and cross-price elasticity of demand for Hass and other avocado varieties from Carmen and Craft's (1998) data. The own-price elasticity of demand for Hass was calculated as -1.2, and for other varieties it was -2.6 (Table 1). The elasticity of demand for Hass with respect to the changes in the price of other varieties was 0.4 and the elasticity of demand for other varieties with respect to the price of Hass was 1.8. From analyses performed by Carmen and Craft (1998), the short-run elasticity of supply was 0.15 and the long-run elasticity of supply was 1.5 for the USA. The elasticity of supply was 2.0 for imports for Hass avocados, and -1.75 for exports of other varieties of avocados.

Supply shares were calculated based on a three-year average (1994–1997) of production (USDA, 2000; California Avocado Commission, 1994–2000), imports (Food and Agriculture Organization, 2000), and exports (Food and Agriculture Organization, 2000) (Table 2). Production shares were also calculated using a 3-year average (1994–1997) (USDA, 2000) (Table 2). A 3 year average was used because it allowed a sufficient amount of time to control for annual variations in production due to weather, yield variations, etc., but short enough to prevent trends in prices, acreage, production, etc. from biasing the baseline market equilibrium point.

Within California, many producers with acreage more than 10 miles from the coast, either did not have an *S. perseae* infestation, or did not have an infestation severe enough to warrant treatment (Hoddle, unpublished). Acreage susceptible to thrips infestations was determined from the questionnaires of growers in Ventura and San Diego Counties. All producers within 10 miles of the coast have economically damaging *S. perseae* populations and about one-third of producers with orchards more than 10 miles inland have *S. perseae* infestations severe enough to warrant treatment. The share of infested and uninfested production in California was calculated from data on the amount of avocado acreage located within each region in California

Table 1
Parameter values for model

Parameter		
Name	In model	Value
Elasticity of demand		
Hass own price	η_{hh}	−1.2
Hass with respect to the price of other varieties	η_{ho}	0.4
Other varieties own price	η_{oo}	−2.6
Other varieties with respect to the price of Hass	η_{oh}	1.8
Elasticity of supply		
Hass produced by CA	ε_{hc}	short run = 0.15, long run = 1.5
Hass from imports	ε_{hm}	2
Other varieties produced by CA	ε_{oc}	short run = 0.15, long run = 1.5
Other varieties exported	ε_{oe}	−1.75
Other varieties produced by rest of US	ε_{orus}	short run = 0.15, long run = 1.5
USA market shares		
Hass from infested producers in CA	λ_{hic}	76.4
Hass from uninfested producers in CA	λ_{huc}	11.4
Hass imported	λ_{hm}	12.2
Other varieties from infested producers in CA	λ_{oic}	70
Other varieties from uninfested producers in CA	λ_{ouc}	10.4
Other varieties from rest of US	λ_{orus}	19.6
Allocation shares of other varieties produced by rest of US		
Production to USA market	γ_{ous}	19.2
Production exported	γ_{oe}	80.8

Table 2
Price and quantity variables[a]

	1994/95	1995/96	1996/97	Average
California production of Hass	139,500	153,900	150,300	147,900
California production of other varieties	15,500	17,100	16,700	16,430
Production of other varieties by rest of US	20,250	19,250	23,700	21,100
Imports of Hass	21,710	16,850	23,050	21,000
Exports of other varieties	9650	23,100	17,760	16,800
Price of Hass	\$1500	\$1440	\$1670	\$1535
Price of other varieties	\$1330	\$775	\$550	\$870

[a] Quantity figures are in short tons (2000 lbs) and price is in dollars (US) per short ton.
Sources: California Avocado Commission (1998, 1999) and California Avocado Society, USDA Fruit and Nut Yearbook, FAO.

provided by the California Avocado Commission (Steve Peirce, personal communication 2001).

2.4. Calculating the change in producer welfare

The changes in market price and quantity variables were used to calculate the new equilibrium market quantities and prices, and the new production levels by infested and uninfested producers. Once the new equilibrium was calculated, the change in producer welfare (area abcd in Fig. 1). was calculated as

$$0.5((NP_{jt} - OP_j) - (OP_j\hat{C}_j))(OT_{ji} + NT_{jit}), \tag{3.1}$$

where NP is the new price of avocado fruit, OP the original (pre-infestation) price of avocado fruit, NT the new production level of avocado fruit, OT the original production level of avocado fruit, $\hat{C}$ is the percentage increase in industry costs due to the establishment of *S. perseae*, j is equal to Hass or other varieties, i is equal to infested or uninfested production region, and t is equal to the short- or long-run time period (see Alston et al., 1995, for more details on the derivation of equations to calculate the change in producer welfare). For uninfested producers, $\hat{C}_j$ is equal to zero. This calculation is based on a parallel shift up of the supply curve around the initial equilibrium point. If the supply curve pivots up, then the losses in producer welfare would be smaller (Miller et al., 1988). However, the methods described by Alston et al. (1995) to calculate the change in welfare can no longer be used (Gotsch and Wohlgenant, 2001).

3. Results

3.1. Change in market quantity supplied and price

The increased costs of avocado production for infested growers due to *S. perseae* caused production of Hass and other varieties to decrease in both the short- and long-run analyses (Table 3). Hass production by producers infested with thrips declined by 0.62% in the short run. However, as producers adapted to the higher costs of production in the long run by removing acreage, annual production declined by 3.7%. California production of other avocado varieties by infested producers showed a similar decline with production falling by 0.02% in the short run, and 1.23% in the long run (Table 3). This decrease in California avocado production caused market prices for other varieties to increase, with long run price increases being greater than in the short run due to the greater decrease in market supply in the long run. Hass avocado prices increased by 2.04% in the long run, but only 0.38% in the short run. The price of other avocado varieties increased by 0.82% in the long run, but only 0.14% in the short run. This increase in price caused imports of Hass to increase, production of other non-Hass avocado varieties by Florida and Hawaii to increase, and exports of other non-Hass varieties to decrease as a larger share of production from Florida and Hawaii was marketed in the USA (Table 3).

Because imports and production by growers without an *S. perseae* infestation increased, the decline in USA market supply of Hass avocados was less than the decline in production by infested growers (Table 3). In the long run, the decline in market supply of Hass avocados was only 2.12%. For other varieties, the increased supply from Florida, Hawaii, and uninfested producers in California was able to replace a portion of lost production by infested producers. Therefore, the long-run decline in the USA supply of other varieties of avocados was only 1.31% even though production by producers infested with thrips declined by 5.52%.

The percentage changes in the quantity and price variables produced by the model were used to calculate the new market equilibrium values and production levels in order to assess the welfare losses and gains to the USA avocado industry using Eq. (3.1). The annual losses for producers with a thrips infestation were estimated to be \$8.11 million (US) in the short run and \$4.78 million (US) in the long run (Table 4). Higher prices reduced losses for infested producers in the long

Table 4
Avocado industry losses

	Time period	
	Short run (\$ million (US))	Long run (\$ million (US))
Hass — infested producers	−8.11	−4.78
Hass — uninfested producers	0.11	0.61
Other varieties — infested producers	−0.54	−0.44
Other varieties — uninfested producers	0.03	0.16
Net losses — USA	−8.51	−4.45

Table 3
Percentage change in endogenous variables

Variable name	Percentage change					
	Original value (\$)	Var. in model	Value		New value (\$)	
			SR (%)	LR (%)	SR \$(US)	LR \$(US)
USA market quantity of Hass	168,400	$\hat{D}_h$ $\hat{S}_h$	−0.40	−2.12	167,728	164,835
USA market quantity of other varieties	20,400	$\hat{D}_o$ $\hat{S}_o$	−0.22	−1.31	20,354	20,133
USA market price for Hass	1535	$\hat{P}_h$	0.38	2.04	1541	1566
USA market price for other varieties	870	$\hat{P}_o$	0.14	0.82	871	877
California production of Hass by infested producers	128,675	$\hat{T}_{hic}$	−0.62	−3.70	127,878	123,918
California production of Hass by uninfested producers	19,190	$\hat{T}_{huc}$	0.06	3.05	19,238	19,814
California production of other varieties by infested producers	14,270	$\hat{T}_{oic}$	−0.65	−5.52	14,175	13,480
California production of other varieties by uninfested producers	2130	$\hat{T}_{ouc}$	0.02	1.23	2132	2158
USA imports of Hass	20,500	$\hat{M}_h$	0.55	2.94	20,613	21,102
Rest of US production of other varieties.	20,800	$\hat{T}_{orus}$	0.02	1.23	20,805	21,055
Quantity supplied of other varieties by rest of US to US	4000	$\hat{S}_{orus}$	1.18	12.38	4047	4495
Quantity exported of other varieties by rest of US to US	16,800	$\hat{E}_o$	−0.25	−1.43	16,757	16,560

run even though less fruit was being produced in California. The losses associated with the production of other varieties of avocados (i.e., non-Hass fruit) in California by infested producers were $540,000 (US) in the short run and $440,000 (US) in the long run (Table 4). The total decline in welfare for growers with a thrips infestation was estimated at $8.65 million (US) in the short run and $5.22 million (US) in the long run.

With lower fruit production by growers having to manage *S. perseae*, USA avocado market prices rose, and California producers without a thrips infestation, and growers in Florida and Hawaii which lack *S. perseae* were better off. Annual producer gains in these groups were estimated at $140,000 (US) in the short run and $610,000 (US) in the long run. Due to the large share of the avocado market by producers that have an *S. perseae* infestation, the net loss to the USA avocado industry was negative. The annual net loss calculated by the model was $8.51 million (US) in the short run and $4.45 million (US) in the long run.

4. Discussion

The establishment of an exotic pest affects many groups with linkages to the affected agricultural commodity. The increase in producer costs for avocado production by infested producers resulted directly from the establishment of *S. perseae* and the subsequent need for insecticidal control to reduce crop loses. However, the impact on uninfested producers was positive as they obtained higher prices for their fruit.

An additional substantial financial burden on the California avocado industry is imposed as producer-derived research funds are diverted from plant breeding and management programs which promote long-term productivity, to research programs that develop short-term strategies to control new pests. Currently, California lacks an effective indigenous natural enemy guild that can control *S. perseae*. Therefore, USA-EPA Section 18 Registrations and Special Local Needs Permits have been sought and granted to provide producers legal access to pesticides not previously registered for use in California avocado orchards to control *S. perseae*. Application processes for use of unregistered pesticides in California are not inconsequential and are demanding of time and money (Hoddle et al., 2002b).

Increased reliance and use of pesticides for *S. perseae* control increases the likelihood of resistance development, destruction of beneficial non-target organisms, and environmental contamination. Alternatively, biological control may provide cost-effective and environmentally benign long-term control of *S. perseae*, and natural enemies could be integrated with other techniques to control additional avocado pests that will become established in the future. This integrated pest management approach assumes that effective natural enemies of *S. perseae* can be located, introduced, and established in California, and these biological control agents will reduce pest densities to non-damaging levels.

The threat of new avocado pests of exotic origin establishing in California has increased substantially with the recent legalization of limited avocado imports from Mexico into the USA, a trade practice that had been banned since 1914 to prevent the unwanted introduction of pestiferous arthropods, especially *Anastrepha* sp. (Diptera: Tephritidae) that infest fruit (Morse et al., 1995). Entry of Hass avocado fruit into the USA is regulated under 7 CFR 319.56, known as the Fruits and Vegetables Quarantine, or Quarantine 56. In 1997, the federal Fruits and Vegetables Quarantine was amended to allow the provisional entry of Mexican Hass avocados into 19 northeastern USA states from November through February. As of June 2001, avocados from Mexican orchards certified pest-free may be imported into 31 northeastern USA states from October 15 through April 15. Mexican Hass avocado imports have increased total Hass imports by over 60% since the ruling became effective.

Over 60 species of phytophagous thrips in at least 17 genera have been recorded from avocados in areas outside of California (Hoddle et al., 2002a). A total of 38 phytophagous thrips species have been collected from avocados in Mexico by Johansen et al. (1999), but only seven species, *Frankliniella bruneri*, *F. chamulae*, *Heliothrips haemorrhoidalis*, *Pseudophilothrips perseae*, *Scirtothrips aguacatae*, *S. kupandae*, and *S. perseae* were considered pests (Hernández et al., 2000). The validity of new *Scirtothrips* species collected from avocados in Mexico and described in a recent taxonomic review (Johansen and Mojica-Guzmán, 1998) has been questioned as species designations were made according to morphological characters that exhibit high variation amongst individuals of the same species (Mound and zur Strassen, 2001). Consequently, deficits in knowledge on the taxonomy, ecology, and biology of the arthropod fauna on avocados in exporting countries may render any mitigation of accidental pest importation practices ineffectual. Increased importation of avocados from outside of California could result in the establishment of additional invasive pest species and further exacerbate the annual long-run costs of $4.5 million (US) to the California avocado industry that are currently caused by a single exotic pest, *S. perseae*.

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